Cosmology with Primordial Black Holes

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Two competing ways of the cosmic conundrum resolution

• A. Traditional astrophysical point of view: BH formation proceeds by formation of BHs by stellar collapse or matter accretion to galactic centres. Unjustified assumptions are demanded, invented just for the case, contradicting established physics: **super Eddington accretion, direct collapse, sleeping BHs,** but still unable to explain many pieces of data. **According to my estemed colleague: this is similar to epicycles in the ancient astronomical Ptolemaic model.**

• B. Explanation of observations by primordial BHs, created in the early universe prior to star birth. Very well confirmed or supported by "experiment" (observational data), **in particular, predicted log-normal mass spectrum of PBHs,** abundant antimatter in our Galaxy (in particular, of antinuclej, antistars and possible star-antistar annihilation, and supermassive black holes (SMPH) in (almost) empty space or in very small galaxies in contemporary and early universe.

Fritz Zwicky discovered dark matter in the 30th and was badly criticised by the community. He referred contemptuously to **"the useless trash in the bulging astronomical journals"**, saying **"Astronomers are spherical bastards. No matter how you look at them they are just bastards."**

Better late than never

Pablo G. Perez-Gonzalez, *et al* **"The rise of the galactic empire: ultraviolet luminosity functions at $z \sim 17$ and $z \sim 25$ estimated with the MIDIS+NGDEEP ultra-deep JWST/NIRCam dataset"**
arXiv:2503.15594 [astro-ph.GA]
Quoting the authors: **Such early objects can be only primordial black holes!**

Maybe not all members of the community are "spherical bastards".

Who was first the chicken or the egg?

In other words: primordial black holes (PBH) or galaxies?
It is usually assumed that supermassive black holes (SMBH) are created by matter accretion to excessive density in galactic centres. However, the necessary time is much larger than the universe age, even for the contemporary universe, with the age about 15 billion years, and the 20 times younger universe at $z \sim 10$.
These and plenty of other facts present strong evidence in favour of the **inverted mechanism of galaxy formation:** firstly PBH were born in the very early universe at prestellar epoch and later they seeded galaxy creation, according to A.Dolgov, J.Silk, PRD 47 (1993) 4244 (DS), "Baryon isocurvature fluctuations at small scale and baryonic **dark matter**";
A.Dolgov, M. Kawasaki, N. Kevlishvili (DKK), NPB807 (2009) 229, "Inhomogeneous baryogenesis, **cosmic antimatter,** and dark matter";
The 30 year old DS idea of seeding, but based on direct collapse assumption and super-Eddington accretion, (both at odds with well established canonical physics) was rediscovered in several recent publications, under the pressure of the NASA Hubble Space Telescope (HST) and the NASA James Webb Telescope (JWST) observations of the early universe at $z = 5 - 15$.

Black holes who are they?

Existence of black holes was ingeniously predicted in 1783 by John Michell, an English country parson, famous for many other discoveries in physics.
He noticed that there could be stellar bodies so massive that they have escape velocity larger than the speed of light. Hence such objects neither shine nor reflect light, and it would be impossible to observe them directly.
Michell called such, not emitting radiation stars as **"dark stars".** According to his idea a single dark star would be invisible, but if a double system of a dark and a usual star is formed, one may identify dark star observing the other one rotating around "nothing".
This is one of possible ways to observe black holes at the present time, among many others.

General relativity and BHs

Four known exact solution describing all types of BHs:

- Schwarzschild (1916), BH with $Q = J = 0$.
- Reissner-Nordström (1916, 1918) $J = 0, \; Q \neq 0$.
- Kerr, (1963), $Q = 0, J \neq 0$.
- Kerr–Newman (1965) $J \neq 0$, $Q \neq 0$.

BHs have only three types of "hairs" that may be observed outside BH:

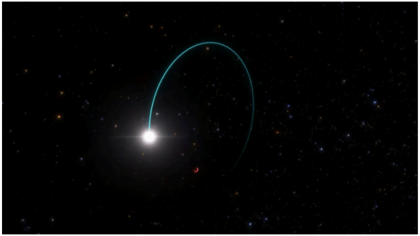
- 1. Gravitational field created by mass, M, asymptotically at large distances tending to the Newtonian limit.
- 2. Electric field created by charge Q, tending to the Coulomb one.
- 3. Field induced by rotation, absent in Newtonian gravity.

If photon mass is non-zero, no matter how tiny, electric field of BH should vanish faster than cosmological time. No continuous limit to $m_\gamma = 0$.
A.D. Dolgov, H. Maeda, T. Torii, hep-ph/0210267 [hep-ph];
A.D. Dolgov, K.S. Gudkova, Phys. Lett. B810 (2020) 135844.

Massive photons could create electrically charged and accelerated universe, thanks to Coulomb repulsion?

Black hole observations

Star rotating around nothing, exactly as envisaged by John Michel.
It appeared a consistent gravitational tug from a hitherto unknown companion was disrupting the star's motion. Known to weigh roughly **33 times our Sun,** the cosmic behemoth is the heaviest stellar-mass black hole yet found in the Milky Way. **Quite unusual for astrophysical BH.**
EAS2024, European Astronomical Society Annual Meeting, held 1-5 July, 2024 in Padova, Italy. Online at https://eas.unige.ch/EAS2024/.



An artist's conception shows the orbits of both the star (in blue) and the black hole (in red), dubbed Gaia BH3, around their common center of mass. Credit: ESO/L. Calçada/Space Engine (spaceengine.org)

BH observations via interaction with surrounding matter

• BHs evaporate and shine (Hawking radiation), though nobody yet saw it.
• Near-solar mass BHs are observed by X-rays from the accreting matter.
• Gravitational lensing by BH, rise of background star brightness, that's how $0.5M_\odot$ MACHOs have been discovered. Could not be created by stellar collapse.
• Mass estimates via star motion around BH, as e.g. in our Galaxy.
• Quasars (QSO), supermassive black holes, that radiate as thousands galaxies, $\boldsymbol{L_{QSO}} = 10^{46} - 10^{47}$ erg/sec, i.e. $10^{13} L_\odot$, though they are practically point-like, their size is about $10^9 - 10^{10}$ km, i.e. smaller than the Solar System. The mechanism of QSO radiation is the process of ultrarelativistic particle collisions in the process of matter accretion. QSOs shine until they consume all "food" around and remain almost in desert, as e.g. BH in the center of our Galaxy.
• All these methods however only allow to measure the mass inside small central volume. According to General Relativity **theory** there must be a BH inside.
• **NB. So strictly speaking BH existence was not proven by "experiment".**
• **Now LIGO/Virgo/KAGRA registration of gravitational waves from BH binaries made a first direct "photo" of the Schwarzschild metric and presents strong evidence that the sources are PBHs.**

BH types by formation mechanisms

1. Astrophysical black holes,
created by the collapse of a star which exhausted its nuclear fuel. The expected masses should start immediately **above** the neutron star mass, i.e. about $3M_\odot$, but noticeably below $100M_\odot$. Instead we observe that the BH mass spectrum in the galaxy has maximum at $M \approx 8M_\odot$ with the width $\sim (1-2)M_\odot$. The result is somewhat surprising but an explanations in the conventional astrophysical frameworks is possible.
Recently LIGO/Virgo discovered BHs with masses close to $100M_\odot$. Their astrophysical origin was considered **impossible due to huge mass loss in the process of collapse, see below.** Exotic formation mechanisms are needed.
No problem if $100M_\odot$ BH is primordial.

BH created by accretion

2. BH formed by accretion to the mass excess in the galactic center.
In any large galaxy there exists a supermassive BH (SMBH) at the center, with masses varying from a few millions $M_\odot$ (e.g. Milky Way) up to almost hundred billions $M_\odot$. **However, the conventional accretion mechanisms are not efficient enough to create such monsters during the universe life-time, $t_U \approx 14.6$ Gyr. At least 10-fold longer time is necessary,** see e.g. E.M. Murchikova, et al Nature 570, 83 (2019);
to say nothing about SMBH in 20 times younger universe, observed in impressive numbers by HST and JWST.
Contradiction between observations and canonical theory is neatly solved if the universe is populated by primordial black holes (PBH) that seeded formation of cosmic structures.

Primordial Black Holes

3. Primordial black holes (PBH) created during pre-stellar epoch

The idea of the primordial black hole (PBH) i.e. of black holes which could be formed the early universe prior to star formation was first put forward by Zeldovich and Novikov: "The Hypothesis of Cores Retarded During Expansion and the Hot Cosmological Model", Astronomicheskij Zhurnal, 43 (1966) 758, Soviet Astronomy, AJ.10(4):602–603;(1967).

According to their idea, the density contrast in the early universe inside the bubble with radius equal to the cosmological horizon might accidentally happen to be large, $\delta\varrho/\varrho \approx 1$, then that piece of volume would find itself inside its gravitational radius i.e. it became a PBH, decoupled from the cosmological expansion.

Elaborated later in S. Hawking, "Gravitationally collapsed objects of **very low mass",** Mon. Not. Roy. Astron. Soc. **152**, 75 (1971).

B. J. Carr and S. W. Hawking, "Black holes in the early Universe," Mon. Not. Roy. Astron. Soc. **168**, 399 (1974).

PBHs are rejected by astrophysical establishment. Why?! However there just appeared a paper where the author-astronomer mentioned possible PBH!!!

BH types by masses

There is the following conventional division of black holes by their masses:

1. Supermassive black holes (SMBH): $M = (10^6 - 10^{11}) M_\odot$.
2. Intermediate mass black holes (IMBH): $M = (10^2 - 10^5) M_\odot$.
3. Solar mass black holes: masses from a fraction of $M_\odot$ up to $100 M_\odot$.

The origin of most of these BHs is unclear in the conventional approach, except maybe of the BHs with masses of a few solar masses, that might be astrophysical. Highly unexpected is great abundance of IMBH which are being abundantly observed at the present day universe during last few years. **Unclear origin.**

The suggestion that (almost) all black holes in the universe are primordial strongly reduce or even eliminate the tension.

Log-normal mass spectrum

The log-normal mass spectrum of PBHs was predicted by DS in 1993 and further developed in 2009 by DKK

$$\frac{dN}{dM} = \mu^2 \exp\left[-\gamma \ln^2(M/M_0)\right],$$

confirmed by LiGO/Virgo/Kagra with very good precision, see below.
According to DS and DKK initial large isocurvature perturbations of baryonic number are generated at inflationary stage, transformed into density perturbations when massless quarks turned into heavy protons and neutrons.
Hence M_0 should be equal to horizon mass at the QCD phase transition:
$\mathrm{M_0} \sim 10\mathrm{M_\odot}$, as predicted in A.Dolgov, K.Postnov, "Why the mean mass of primordial black hole distribution is close to $10M_\odot$". JCAP 07 (2020) 063.
The horizon mass at QCD p.t. is close to $10M_\odot$, for $\mu = 0$. At larger chemical potential T_{pt} is smaller and M_{hor} is larger, namely, $\approx 17M_\odot$, according to lattice calculations (I. Arefyeva), **exactly what is observed, see below.**

Crisis in cosmology

Conventional ΛCDM cosmology encounters serious difficulties describing astronomical observations during **all the history** of the universe,
starting from our time with the universe age about 15 billion years,
and back to the past down to $\sim$ 300 million years discovered recently by HST, JWST, and ALMA at high redshifts $z \sim 10$**.**

The inconsistenies discovered earlier are reviewed in 2018: A.D. "Massive and supermassive black holes in the contemporary and early Universe and problems in cosmology and astrophysics", Phys. Usp. 61 (2018) 2, 115.

The tension, between the canonical theory and observations, that existed during **all life-time of the universe,** is completely eliminated if the universe is populated by primordial black holes (PBH) that **seeded** formation of cosmic structures.

Confirmation by "experiment"

• The calculated mass spectrum of PBH very well agrees with the data.
• The early galaxy formation observed by HST and JWST is explained if galaxies are SEEDED by BHs, as it is also rediscovered in several papers of the last years.
• Discovery of IMBH, with $\boldsymbol{M} \sim (10^3 - 10^5)\boldsymbol{M}_\odot$ in dwarfs and globular clusters, **predicted** in AD & K. Postnov. "Globular Cluster **Seeding** by Primordial Black Hole Population", JCAP 04 (2017) 036, e-Print: 1702.07621 [astro-ph.CO].
Critical prediction: IMBHs in Magellanic Clouds? Recently observed!
• SMBH in almost empty space or in tiny galaxies.

Galactic antimatter:
• Noticeable antimatter population of the Galaxy is anticipated and confirmed by the observations of **positrons, antinuclei, and antistars.**
• The observation of gamma burster, that could be star-antistar collision!!!.
Nickname: **Brightest of All Time (BOAT)**

Problems of the contemporary universe. Summary.

1. Supermassive BH (SMBH) in all large galaxies. Too short time (15 billion year) for their formation through the conventional accretion mechanism.
2. Huge SMBH in small galaxies and even in (almost) EMPTY space. No material for their creation. Pushed out of large galaxies? Wandering BHs?
3. Too old stars, older than the Galaxy and maybe one **older** than the universe?
4. MACHOs, non-luminous objects, $M \sim 0.5 M_\odot$, observed through microlensing.
5. Problems of BH mass spectrum in the Galaxy with $(M = 7.8 \pm 1.2) M_\odot$.
6. Origin and properties of the sources of the observed gravitational waves.
7. Origin of intermediate mass BH (IMBH) with masses $(10^3 - 10^5) M_\odot$. Plenty of them are observed everywhere in the universe, in particular in dwarfs and globular clusters, as predicted by AD & K. Postnov.
8. Discovery of BH with $M \approx 100 M_\odot$, that is strictly forbidden but nevertheless observed by LIGO/Virgo.
9. Strange stars in the Galaxy, too fast and with unusual chemistry.

Problems of the early universe

Serious problems, similar to those recently found by JWST, are known already for many years. HST discovered that the early universe, at $z = 6 - 7$ is too densely populated with quasars, alias SMBH, supernovae, gamma-bursters and it is very dusty. **No understanding in conventional cosmology how all these creature were created in such a short time.**

"Hubble" sees the universe up to $z = 6 - 7$, but accidentally a galaxy at $z \approx 12$ has been discovered for which both Hubble and Webb are in good agreement.

Huge BHs in small galaxies discovered in the early universe (as well as in the contemporary one). Such huge BHs could not be created by the accretion of matter to galactic center, since the amount of material is too small.
Quite a few SMBH are observed in practically empty space!!!

All the problems are neatly solved if the universe is populated by primordial black holes (PBH) and the astrophysically large bubbles with very high baryonic density, according to DS and DKK.

Impossible galaxies

I. Labbé, P. van Dokkum, E. Nelson, *et al*, "A population of red candidate massive galaxies 600 Myr after the Big Bang", Nature, 616, 7956, (2022), arXiv:2207.12446. Six candidate massive galaxies (stellar mass $> 10^{10}$ solar masses) at $7.4 \lesssim z \lesssim 9.1$ 500–700 Myr after the Big Bang, one galaxy with a possible stellar mass of $\sim 10^{11} M_{\odot}$, too massive to be created in so early universe. According to the authors it is **impossible** to create so well developed galaxies. **NB: "May be they are supermassive black holes of the kind never seen before. That might mean a revision of usual understanding of black holes." Well agrees with our suggestion of PBHs.**

Too small stellar mass of early galaxies

Observations of the early galaxies with stellar mass too high, by factor up to 100 w.r.t. to the central BH mass. It means that the galaxies are in the process of formation and have not yet reached the final mass value - a strong argument in favor of the inverted mechanism of galaxy formation.

- According to: R. Endsley et al, MNRAS, 250, 4609 (2023), "ALMA (Atacama Large Millimeter Array") **The ratio of the central SMBH mass,** $M_{BH} =\sim 1.6 \times 10^9 M_\odot$ to the total mass of stars in an early galaxy $M_* = 1.7 \times 10^{11} M_\odot$ is unusually high: $\boldsymbol{r_{early} \equiv M_{BH}/M_* \sim 10^{-2}}$**,** while in the contemporary galaxies this ratio is $\mathrm{r_{now}} \sim 10^{-6}$.
- J. Matthee, *et al*, 2412.02846 [astro-ph.GA]. "Environmental Evidence for Overly Massive Black Holes in Low Mass Galaxies and a Black Hole - Halo Mass Relation at $z \sim 5$". **At** $z = 4 - 5$ **seven BHs with masses** $\sim (4 - 15) \times 10^6 M_\odot$ **are observed,** the black holes seem too massive compared to the mass of the stars in the galaxies that host them, about 10% of the stellar mass.

Primordial BHs seeding galaxy formation easily resolve this conundrum. This is not that BHs are too heavy, but the galaxies are too light.

More galaxies with too small stellar masses

• F. Pacucci, B. Nguyen, S. Carniani *et al* "JWST CEERS and JADES Active Galaxies at $z = 4 - 7$ Violate the Local $M_* - M_{BH}$ Relation at $> 3\sigma$: Implications for Low-mass Black Holes and Seeding Models", The Ap.J. Letters, 957:L3, 2023.
Black holes are **overmassive by factor 10-100** compared to their low-z counterparts in galactic hosts of the same stellar mass.
• M.A. Marshall, *et al*, "GA-NIFS & EIGER: A merging quasar host at $z = 7$ with an overmassive black hole", arXiv:2410.11035.
The mass of the central black hole is $\boldsymbol{M_{BH}} \approx 1.4 \times 10^9 \boldsymbol{M_\odot}$, only twice smaller than the host stellar mass equal to $\boldsymbol{M_*} \approx 2.6 \times 10^9 \boldsymbol{M_\odot}$, versus about 0.1 percent for central black holes in modern giant galaxies. The stellar mass of the Milky Way is $6 \cdot 10^{10} M_\odot$ and the central BH mass is $5 \cdot 10^5 M_\odot$.

It is hard to imagine that the central BH was created by accretion of matter to the galactic center, as is commonly assumed.

From super- to sub- Eddington accretion

"A dormant, overmassive black hole in the early Universe", I. Juodzbalis, R. Maiolino, W.M. Baker, *et al*, Nature, Volume 636, Issue 8043, pp. 594-597, 2403.03872: **Recent observations have found a large number of SMBHs already in place in the first few hundred million years after Big Bang. The channels of formation and growth of these early, massive black holes are not clear, with scenarios ranging from heavy seeds to light seeds experiencing bursts of high accretion rate.**

The detection, from the JADES survey, of broad Hα emission in a galaxy at $z = 6.68$, which traces a black hole with mass of $\sim 4 \times 10^8 M_\odot$ and accreting at a rate of **only 0.02 times the Eddington limit.**

$M_{BH}/M_* \approx 0.4$**, i.e.** 10^3 **times above the local relation**. See also previous slides about huge BH in small galaxies.

There are indications to a much larger population of dormant black holes around the epoch of reionization. Its properties are consistent with scenarios in which short bursts of **super-Eddington accretion have resulted in black hole overgrowth and massive gas expulsion from the accretion disk; in between bursts, black holes spend most of their life in a dormant(?!) state.**

Direct collapse out !?

To save direct collapse of cold gas in the early universe is necessary to assume that gas is not heated in the process of compression???!!! **Impossible with canonical, well established particle physics.** Non-interacting Dark Matter?

Possible elimination of direct collapse: M.J. Hayes, J.C. Tan, R.S. Ellis, *et al* "Glimmers in the Cosmic Dawn: A Census of the Youngest Supermassive Black Holes by Photometric Variability", The Astrophysical Journal Letters, Volume 971, Issue 1, id.L16.

The variability estimate of n_{SMBH} at $z = (6-7) \geq 8 \times 10^{-3}$ Mpc^{-3} places constraints on d_{iso} to be $<<$ 100kpc. It requires the halo mass threshold for SMBH formation to be $<< 3 \times 10^{10} M_{\odot}$. However, such models begin to have more severe tension by having significantly greater abundance than the $z = 0$ estimate of n_{SMBH}.

Finally, the estimate of the necessary value of n_{SMBH} is about 100 times greater than the direct collapse prediction of Chon et al. (2016) and at least 10^4 times greater than that of Wise et al. (2019).

Unexpectedly light black holes

• "Observation of Gravitational Waves from the Coalescence of a $2.5 - 4.5\ M_\odot$ Compact Object and a Neutron Star",
The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration Report-no: LIGO-P2300352, arXiv:2404.04248:
(2.5-4.5) $M_\odot$ and (1.2-2.0) $M_\odot$
The masses do not fit any conventional hypothesis, if they are not primordial.

• In T. Jayasinghe, *et al*. MNRAS, **504**, (2021), Issue 2, p.2577 one of the lightest black holes is detected, that **should not exist.** It is in the middle of the mass gap, weighing at about three solar masses with the mass $M_{(BH?)} = (3.04 \pm 0.06) M_\odot$. It is impossible to explain existence of such a light BH by stellar evolution, light stars turn into neutron stars but not into BHs.

• K.C. Sahu, *et al*, Ap. J., **983**, Issue 2, id.104, 13. There is an isolated stellar-mass black hole in the Milky Way with $M = (7.15 \pm 0.83) M_\odot$???

They all can be PBHs.

Early (impossible!) quasars in empty space

Final blow: six early quasars in empty space. Anna-Christina Eilers *et al*, "EIGER. VI. The Correlation Function, Host Halo Mass, and Duty Cycle of Luminous Quasars at $z \gtrsim 6$", the Astrophysical Journal, Volume 974, Number 2.

The data indicate that

(a) luminous quasars do not necessarily reside within the most overdense regions in the early Universe,

(b) the UV-luminous duty cycle of quasar activity at these redshifts is $f_{duty} \ll 1$. Such short quasar activity timescales challenge our understanding of early supermassive black hole growth.

Using the James Webb Space Telescope, astronomers have peered back 13 billion years to discover **surprisingly lonely** supermassive black hole-powered quasars.

Eilers: "**Some of them seem to be sitting in the middle of nowhere**

It's difficutl **(impossible?)** to explain how these quasars could have grown so big if they appear to have nothing to feed from.

"Contrary to previous belief, we find, on average, these quasars are not necessarily in those highest-density regions of the early universe."

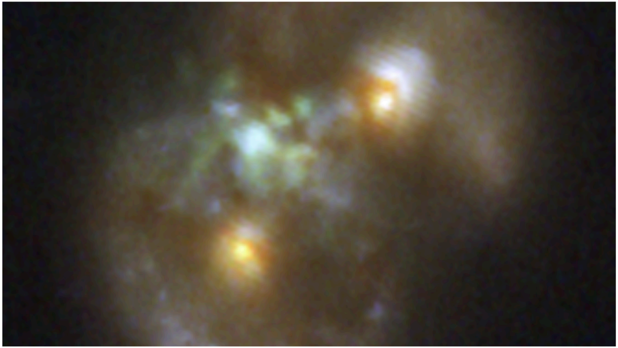
Surely they are primordial SMBH.

Summary of the impossibles in the early universe

- Impossible (super) Eddington accretion?
- Impossible direct collapse.
- Impossible quasars in empty space.
- Impossible creation of supermassive BH in very young universe.
- Impossibly light BH.
- Impossibly high ratio of galactic stellar mass to the mass of the central BH
- Impossible high density of IMBH.

- **PBHs make the impossibles possible.**

Two galaxies with SMBH inside and larger SMBH between



The Infinity Galaxy, the result of two colliding spiral galaxies, is composed of two rings of stars (seen as ovals at upper right and lower left). The two nuclei of the spiral galaxies are seen represented in yellow within the rings. Glowing hydrogen that has been stripped of its electrons between the two galaxies appears green. Astronomers have detected a million-solar-mass black hole that seems to be embedded within this large swath of ionized gas. They suggest that the black hole might have formed there through a process known as direct collapse. This image from NASA's James Webb Space Telescope's NIRCam (Near-Infrared Camera) represents light at 0.9 microns as blue (F090W), 1.15 and 1.5 microns as green (F115W+F150W), and 2.0 microns as red (F200W).
NASA, ESA, CSA, STScI, P. van Dokkum (Yale University)

Could large SMBH be created by accretion?

Gravitational waves from BH binaries

• GW discovery by LIGO strongly indicate that the sources of GW are PBHs, see e.g. S. Blinnkov, A.D., N. Porayko, K. Postnov, JCAP 1611 (2016), 036 "Solving puzzles of GW150914 by primordial black holes,"

1. Origin of heavy BHs ($\sim 30 M_\odot$)? There appeared much more striking problem of BH with $M \sim 100 M_\odot$. To form so heavy BHs, the progenitors should have $M > 100 M_\odot$ and a low metal abundance to avoid too much mass loss during the evolution. Such heavy stars might be present in young star-forming galaxies but they are not observed in the necessary amount. A possible way out was proposed in J. Ziegler, K. Freese, "Mechanism for nonnuclear energy to fill in the black hole mass gap", Phys.Rev.D 109 (2024) 10, 103042 • e-Print: 2212.13903 based on assumption of dark matter annihilation inside heavy stars.
2. Formation of BH binaries from the original stellar binaries. Recoil momentum?
3. Low spins of the coalescing BHs .

PBHs with observed by LIGO masses may be easily created with sufficient density.

Chirp mass distribution

Intensity of gravitational radiation is determined by chirp mass M_c:

$$L = \frac{32}{5}\, m_{Pl}^2 \left(\frac{M_c\, \omega_{orb}}{m_{Pl}^2} \right)^{10/3},$$

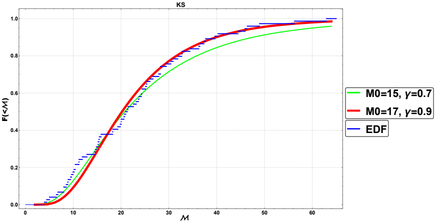
where

$$M_c = \frac{(M_1\, M_2)^{3/5}}{(M_1 + M_2)^{1/5}},$$

The data on the chirp mass distribution of the black holes have been compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum have been analyzed in A.D. Dolgov, *et al* JCAP 12 (2020) 017, e-Print: 2005.00892.
The inferred best-fit mass spectrum parameters, $M_0 = 17 M_\odot$ and $\gamma = 0.9$, fall within the theoretically expected range and shows excellent agreement with observations. On the opposite, binary black hole formation based **on massive binary star evolution** require additional adjustments to reproduce the observed chirp mass distribution.

Chirp mass distribution

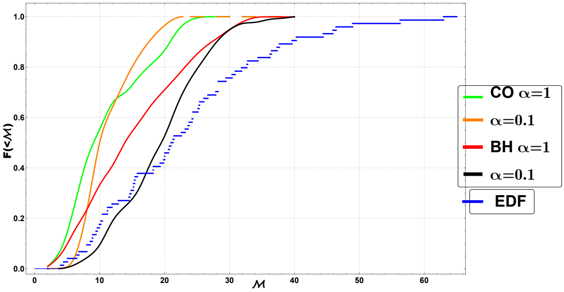
Model distribution $F_{PBH}(< M)$ with parameters $M_0 \approx 17 M_\odot$ and $\gamma \sim 1$ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.



Similar value of the parameters are obtained in M. Raidal et al, JCAP.,2019. Feb. V. 2019, no. 2. P. 018. arXiv:1812.01930 and L. Liu, et al arXiv:2210.16094.
See also K. Postnov and N. Mitichkin, e-Print: 2302.06981.

Chirp mass distribution

Cumulative distributions $F(< M)$ for several **astrophysical** models of binary BH coalescences.



Conclusion: PBHs with log-normal mass spectrum perfectly fit the data. Astrophysical BHs seem to be disfavoured.

Black Dark Matter

The first suggestion PBH might be dark matter "particles" was made by S. Hawking in 1971 "Gravitationally collapsed objects of very low mass", Mon. Not. R. astr. Soc. (1971) 152, 75 and simply repeated later by G. Chapline in 1975 who noticed that low mass PBHs might be abundant in the present-day universe with the density comparable to the density of dark matter. G.F. Chapline, Nature, 253, 251 (1975) "Cosmological effects of primordial black holes". Assumed flat mass spectrum in log interval:

$$dN = N_0 (dM/M)$$

with maximum mass $M_{max} \lesssim 10^{22}$ g, which hits the allowed mass range.
The next one: DS (Mar 13, 1992), Baryon isocurvature fluctuations at small scales and **baryonic dark matter,** with more realistic masses. **First paper with inflation applied to PBH formation, so PBH masses as high as $10^6 M_\odot$, and even higher can be created, log-normal mass spectrum was predicted.**

Constraints on PBHs - B.Carr, F. Kuhnel "Primordial Black Holes as Dark Matter: Recent Developments", arXiv:2006.02838, June 2020
Primordial black holes as dark matter candidates B. Carr, F. Kuhnel SciPost Phys.Lect.Notes 48 (2022), e-Print: 2110.02821 [astro-ph.CO]
Monochromatic mass spectrum of PBHs (model-dependent and have caveats).

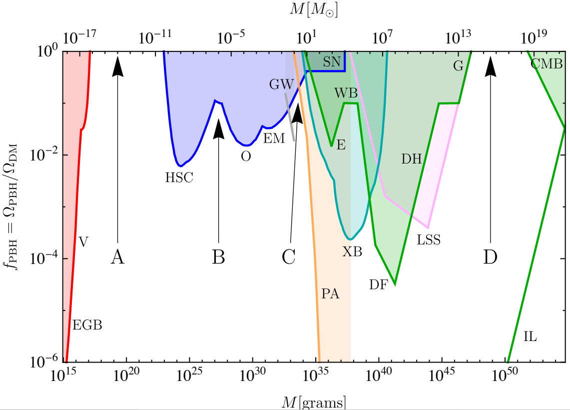


Figure caption

Constraints on $f(M)$ for a **monochromatic** mass function, from evaporations (red), lensing (blue), gravitational waves (GW) (gray), dynamical effects (green), accretion (light blue), CMB distortions (orange) and large-scale structure (purple). Evaporation limits from the extragalactic gamma-ray background (EGB), the Voyager positron flux (V) and annihilation-line radiation from the Galactic centre (GC). Lensing limits from microlensing of supernovae (SN) and of stars in M31 by Subaru (HSC), the Magellanic Clouds by EROS and MACHO (EM) and the Galactic bulge by OGLE (O). Dynamical limits from wide binaries (WB), star clusters in Eridanus II (E), halo dynamical friction (DF), galaxy tidal distortions (G), heating of stars in the Galactic disk (DH) and the CMB dipole (CMB). Large scale structure constraints(LSS). Accretion limits from X-ray binaries (XB) and Planck measurements of CMB distortions (PA). The incredulity limits (IL) correspond to one PBH per relevant environment (galaxy, cluster, Universe). There are four mass windows (A, B, C, D) in which PBHs could have an appreciable density.

Lifting bounds on PBH dark matter

• Extended mass spectrum N. Bellomo, J.L. Bernal, A. Raccanelli, L. Verde, "Primordial Black Holes as Dark Matter: Converting Constraints from Monochromatic to **Extended** Mass Distributions", JCAP 01 (2018) 004.
A window that is closed for a Monochromatic Mass distribution (MMD) can open for an EMD, in particular for log-normal mass spectrum.

• In "Constraints on Primordial Black Holes with **Extended** Mass Functions" F. K*ü*hnel, K. Freese Phys. Rev. D 95 (2017) 8, 083508, e-Print: 1701.07223 there a window in the mass range $10^{-10} M_\odot$ to $10^{-8} M_\odot$ to accommodate for 100% PBH dark matter.

• BH clustering and DM Y. Eroshenko, V. Stasenko, in "Gravitational waves from the merger of two primordial black hole clusters" Symmetry 15 (2023) 3, 637, arXiv:2302.05167, showed that $f_{PBH} = 0.1 - 1$ is not excluded.

(Almost?) all black holes in the universe are primordial.

THE END OF BH PART, NEXT IS inflation and antimatter in the Galaxy.

PBH and inflation

Cosmological inflation allowed for formation of PBH with very large masses. Mass of perturbations inside cosmological horizon grows exponentially, that allows for creation even of supermassive PBHs.

• It was first applied to PBH production in 1993 (DS) [and further developed in by DKK in 2009];

• a year after DS in: B.J. Carr, J.H. Hilbert, J.E. Lidsey, "Black hole relics and inflation: Limits on blue perturbation spectra", Phys.Rev.D 50 (1994) 4853;

• soon after in P. Ivanov, P. Naselsky, I. Novikov (May 10, 1994), "Inflation and primordial black holes as dark matter", PRD 50 (1994) 7173.

An avalanche of papers on inflationary formation of PBH nowadays.
Presently inflationary mechanism of PBH production is commonly used.
However, almost always the calculated mass spectrum is multi-parameter one and quite complicated. **The only exception is the log-normal spectrum predicted by DS, that is perfectly well confirmed by observations.**

Nuffield workshop, 1982, dedicated to inflation

Inflationary cosmology is probably the most important step in understanding of the universe evolution during last 50 years. Solves problems of causality, flatness, perturbations,... creates supermassive PBH

Pioneering papers:

A.A. Starobinsky, A new type of isotropic cosmological model without singularity. R^2-theory. Phys. Lett. 91B, 99 (1980) Received 11/01 1980.

D. Kazanas: Dynamics of the universe and spontaneous symmetry braking. ApJ, 241, L59 (1980), Received 05/05/1980

A. Guth, Inflationary universe: A possible solution to the horizon and flatness problems, PRD 23, 347 – Published 15 January 1981, Received 11/08/1980

A. D. Linde, "A new inflationary universe scenario: A possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems," Phys. Lett. B 108, 389 (1982). Published 04/02/1982.

A. Albrecht, P. J. Steinhardt, "Cosmology for grand unified theories with radiatively induced symmetry breaking," Phys. Rev. Lett. 48, 1220 (1982). Published 26/04/1982.

Density perturbations, spectrum confirmed by observations:

V.F. Mukhanov, G.V. Chibisov, JETP Lett. 33 (1981) 532.

Prehistory of inflation

There is significant "pre-inflationary" literature.
The idea that the universe avoided singularity and underwent exponential period during which the mass of the cosmological matter rose by tens orders of magnitude was discussed by E.B. Gliner ZhETF, 49 (1965) 542 and by E.B. Gliner and I.G. Dymnikova Astronomical Journal Letters, 1 (1975) 7.
De Sitter like (exponentially expanding) non-singular cosmology was considered by V.Ts. Gurovich and A.A. Starobinsly Sov. Phys. JETP 50 (1979) 844; Zh. Eksp. Teor. Fiz. 77 (1979) 1683.
In the last paper inflation was supposed to be induced by radiative corrections to the Einstein equations that could in particular lead to an addition of R^2 term to the classical Hilbert-Einstein action.
The calculations of these corrections were first performed by V.L. Ginzburg, D. A. Kirzhnits, and A. A. Lyubushin, 1971, Zh. Eksp. Teor. Fiz. 60, 451.

Antimatter in the universe and in the Galaxy

The "crazy" by-product of AD and DKK mechanism, namely prediction of antimatter in the Galaxy seems to come true as well.

Astronomical data of the several recent years present strong evidence in favour of notieable antimatter population in our Galaxy including:

• Observation of gamma-rays with energy 0.511 MeV, which surely originate from electron-positron annihilation at rest.

• Very large flux of anti-helium nuclei, observed at AMS.

• **Several stars are found which produce excessive gamma-rays with energies of several hundred MeV which may be interpreted as indication that these stars consist of antimatter.**

Antimatter history

Search for galactic antimatter
B.P. Konstantinov, et al Cosmic Research, 4, 66 (1968);
B.P. Konstantinov, et al Bulletin of the Academy of Sciences of the USSR. Physical series, 33, No,11, 1820 (1969). Strongly criticised by Zeldovich.

Antimatter in the universe:
F. W. Stecker, et al Possible Evidence for the Existence of Antimatter on a Cosmological Scale in the Universe, Phys. Rev. Letters 27, 1469 (1971);
F. W. Stecker, Grand Unification and possible matter-antimatter domain structure in the the universe. Tenth Texas Symposium on Relativistic Astrophysics, p. 69 (1981),

Summary of the situation presented at 2002:
F. W. Stecker, "The Matter-Antimatter Asymmetry of the Universe (keynote address for XIVth Rencontres de Blois)" arXiv:hep-ph/0207323.
A.D. Dolgov, "Cosmological matter antimatter asymmetry and antimatter in the universe", keynote lecture at 14th Rencontres de Blois on Matter - Anti-matter Asymmetry, e-Print: hep- ph/0211260.

Antimatter history

Paul A.M. Dirac: "Theory of electrons and positrons", Nobel Lecture, December 12, 1933: "It is quite possible that... these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."
It seems that now we know ways to distinguish stars from an antistars by observations from the Earth. A.D. Dolgov, V.A. Novikov, M.I. Vysotsky, "How to see an antistar" JETP Lett. 98 (2013) 519, e-Print: 1309.2746
The spectra are not exactly the same, even if CPT is unbroken and the polarization of radiation could be a good indicator or the type of emitted neutrinos/antineutrinos from supernovae.

Antimatter history

Dirac was the second person to talk about antimatter. In 1898, 30 years before Dirac and one year after discovery of electron (J.J. Thomson, 1897) Arthur Schuster (another British physicist) conjectured that there might be other sign electricity, ANTIMATTER, and supposed that there might be entire solar systems, made of antimatter, INDISTINGUISHABLE from ours.
Schuster's wild guess: matter and antimatter are capable to annihilate and produce VAST energy.
He believed that they were gravitationally repulsive having negative mass. Two such objects on close contact should have vanishing mass!?
A. Schuster, Nature, 58 (1898) 367. Potential Matter. Holiday Dream.
"When the year's work is over and all sense of responsibility has left us, who has not occasionally set his fancy free to dream about the unknown, perhaps the unknowable?"
"Astronomy, the oldest and yet most juvenile of the sciences, may still have some surprises in store. May antimatter be commended to its case".

Antimatter in the Galaxy

Based on the conventional approach no antimatter object is expected to be in the Galaxy.

However, it was predicted by DS (1993) and elaborated by DKK (2009) that noticeable amount of antimatter, even antistars might be in the Galaxy.

Bounds on the density of galactic antistars are rather loose, because the annihilation proceeds only on the surface of antistars as analyzed in:

• C.Bambi, A.D. Dolgov, **"Antimatter in the Milky Way",** Nucl.Phys.B 784 (2007) 132-150 • astro-ph/0702350,

• A.D. Dolgov, S.I. Blinnikov, **"Stars and Black Holes from the very Early Universe",** Phys.Rev.D 89 (2014) 2, 021301 • 1309.3395,

• S.I.Blinnikov, A.D., K.A.Postnov, **"Antimatter and antistars in the universe and in the Galaxy",** Phys.Rev.D 92 (2015) 023516 • 1409.5736.

Anti-evidence: cosmic positrons

Observation of intense 0.511 line, a proof of abundant positron population in the Galaxy. In the central region of the Galaxy electron–positron annihilation proceeds **at a surprisingly high rate,** creating the flux:

$$\Phi_{511\ \mathrm{keV}} = 1.07 \pm 0.03 \cdot 10^{-3}\ \mathbf{photons\ cm^{-2}\ s^{-1}}.$$

The width of the line is about 3 keV. Emission mostly goes from the Galactic bulge and at much lower level from the disk,

"Great Annihihilator" in the Galactic bulge.

G. Weidenspointner *et al.*, Astron. Astrophys. **450**, 1013 (2006);

J. Knodlseder *et al.*, Astron. Astrophys. **441**, 513 (2005);

P. Jean *et al.*, Astron. Astrophys. **445**, 579 (2006).

Until recently the commonly accepted explanation was that e^+ are created in the strong magnetic fields of pulsars but the recent results of AMS probably exclude this mechanism, since the spectrum of $\bar{p}$ and e^+ at high energies are identical. L'Aquila Joint Astroparticle Colloquium, 10th November, 2021 by S. Ting.

Anti-evidence: cosmic antinuclei

Registration of anti-helium: **In 2018 AMS-02 announced possible observation of six $\overline{He}^3$ and two $\overline{He}^4$.**

A. Choutko, AMS-02 Collaboration, "AMS Days at La Palma, La Palma, Canary Islands, Spain," (2018).

S. Ting, Latest Results from the AMS Experiment on the International Space Station. Colloquium at CERN, May, 2018.

Recent registration of more events L'Aquila Joint Astroparticle Colloquium, 10th November by S. Ting; and COSPAR 2022, 16-24 July:

7 $\overline{D}$ ($\lesssim$ 15 GeV) and 9 $\overline{He}$, ($\sim$ 50 GeV). **fraction $\overline{He}/He \sim 10^{-9}$, too high.**

Secondary creation of $\overline{He}^4$ is negligibly weak.

Nevertheless S. Ting expressed hope to observe $\overline{Si}$!!!

It is not excluded that the flux of anti-helium is even much higher because low energy $\overline{He}$ may escape registration in AMS.

Deuterium/Helium problem

There is noticeable discrepancy between the large fraction of D with respect to He, if it is assumed that the abundances of D and He are determined by the canonicalBBN with large β (or η).
Indeed in the case of the standard BBN this ratio should be much smaller than unity, but the observed one is practically 1.
On the other hand in our scenario formation of primordial elements takes place inside non-expanding compact stellar-like objects with fixed temperature. If the temperature is sufficiently high, this so called BBN may stop before abundant He formation with almost equal abundances of D and He. One can see that looking at abundances of light elements as a function of temperature. Is it is so, antistars may have equal amount of $\overline{D}$ and $\overline{He}$!!!

Possible discovery of anti-stars in the Galaxy

S. Dupourqué, L. Tibaldo and P. von Ballmoos, Constraints on the antistar fraction in the Solar System neighborhood from the 10-year Fermi Large Area Telescope gamma-ray source catalog,
Phys Rev D.103.083016 103 (2021) 083016

We identify in the catalog 14 antistar candidates not associated with any objects belonging to established gamma-ray source classes and with a spectrum compatible with baryon-antibaryon annihilation.

X-ray signatures of antistars

X-ray signature of antistars in the Galaxy A.E. Bondar, S.I. Blinnikov, A.M. Bykov, A.D. Dolgov, K.A. Postnov e-Print: 2109.12699 [astro-ph.HE], JCAP, Sep 26, 2021,

In astrophysically plausible cases of the interaction of neutral atmospheres or winds from antistars with ionised interstellar gas, the hadronic annihilation **will be preceded by the formation of excited $p\bar{p}$ and $He\bar{p}$ atoms.** These atoms rapidly cascade down to low levels prior to annihilation giving rise to a series of narrow lines which can be associated with the hadronic annihilation gamma-ray emission. The most significant are L (3p-2p) 1.73 keV line (yield more than 90%) from $p\bar{p}$ atoms, and M (4-3) 4.86 keV (yield $\sim$ 60%) and L (3-2) 11.13 keV (yield about 25%) lines from $He^4\bar{p}$ atoms. These lines can be probed in dedicated observations by forthcoming sensitive X-ray spectroscopic missions XRISM and Athena and in wide-field X-ray surveys like SRG/eROSITA all-sky survey.

Antihelium and antistars

A.M. Bykov, K.A. Postnov, A.E. Bondar, S.I. Blinnikov, A.D. Dolgov, "Antistars as possible sources of antihelium cosmic rays", JCAP 08 (2023) 027 • e-Print: 2304.04623 [astro-ph.HE]. Possible sources of antinuclei in cosmic rays from antistars which are predicted in a modified Affleck-Dine baryogenesis scenario by DS (1993) are discussed. The expected fluxes and isotopic content of antinuclei in the GeV cosmic rays produced in scenarios involving antistars are estimated. It is shown that the flux of antihelium cosmic rays reported by the AMS-02 experiment can be explained by Galactic anti-nova outbursts, thermonuclear anti-SN Ia explosions, a collection of flaring antistars, or an extragalactic source with abundances not violating existing gamma-ray and microlensing constraints on the antistar population.

Gamma burster from star-antistar collision!?

Very powerful gamma-ray burster (GRB) was reported in M.E. Ravasio, O.S. Salafia, G. Oganesyan, *et al*, SCIENCE, 25 Jul 2024, **385**, Issue 6707, p. 452; 2303.16223 [astro-ph.HE].

This event got the nickname: the Brightest Of All Time or the bf BOAT. This extremely strong GRB occurred in October 2022. A bright megaelectronvolt emission line was observed, that appeared 280 seconds after the GRB began and then rapidly faded away while shifting to lower energies.

Usually the gamma-ray spectra of GRBs consist of a smooth continuum without absorption or emission lines. The authors interpret this line as having been produced by the annihilation of electron-positron pairs within the relativistic jet produced by the GRB **possibly emerging from star-antistar annihilation !?**

Star-antistar collision, may be a quasi-periodic process of a star-antistar direct contact, explosion forcing them apart, and possible, but not necessary return to each other by gravitational attraction.

PBH Creation Mechanism

SUSY motivated baryogenesis, Affleck and Dine (AD).
SUSY predicts existence of scalars with B $\neq 0$. Such bosons may condense along flat directions of the quartic potential:

$$U_\lambda(\chi) = \lambda|\chi|^4\left(1 - \cos 4\theta\right)$$

and of the mass term, $U_m = m^2\chi^2 + m^{*\,2}\chi^{*\,2}$:

$$U_m(\chi) = m^2|\chi|^2[1 - \cos\left(2\theta + 2\alpha\right)]\,,$$

where $\chi = |\chi|\exp\left(i\theta\right)$ and $m = |m|e^\alpha$. If $\alpha \neq 0$, C and CP are broken.
In GUT SUSY baryonic number is naturally non-conserved - non-invariance of $U(\chi)$ w.r.t. phase rotation.

Creation Mechanism

Initially (after inflation) χ is away from origin and, when inflation is over, starts to evolve down to equilibrium point, $\chi = 0$, according to Newtonian mechanics:

$$\ddot{\chi} + 3H\dot{\chi} + U'(\chi) = 0.$$

Baryonic charge of χ:

$$B_\chi = \dot{\theta}|\chi|^2$$

is analogous to mechanical angular momentum. χ decays transferred baryonic charge to that of quarks in B-conserving process.

AD baryogenesis could lead to baryon asymmetry of order of unity, much larger than the observed 10^{-9}.

Creation Mechanism

If $m \neq 0$, the angular momentum, B, is generated by a different direction of the quartic and quadratic valleys at low χ. If CP-odd phase α is small but non-vanishing, both baryonic and antibaryonic domains might be formed with possible dominance of one of them.
Matter and antimatter objects may exist but globally $B \neq 0$.

Affleck-Dine field χ with CW potential coupled to inflaton Φ (AD and Silk; AD, Kawasaki, Kevlishvili):

$$U = g|\chi|^2(\Phi - \Phi_1)^2 + \lambda|\chi|^4 \ln\left(\frac{|\chi|^2}{\sigma^2}\right)$$
$$+\lambda_1(\chi^4 + h.c.) + (m^2\chi^2 + h.c.).$$

Coupling to inflaton is the general renormalizable one.
When the window to the flat direction is open, near $\Phi = \Phi_1$, the field χ slowly diffuses to large value, according to quantum diffusion equation derived by Starobinsky, generalized to a complex field χ.

Creation Mechanism

If the window to flat direction, when $\Phi \approx \Phi_1$ is open only during a short period, cosmologically small but possibly astronomically large bubbles with high β could be created, occupying a small fraction of the universe, while the rest of the universe has normal $\beta \approx 6 \cdot 10^{-10}$, created by small χ. The mechanism of massive PBH formation quite different from all others. The fundament of PBH creation is build at inflation by making large isocurvature fluctuations at relatively small scales, with practically vanishing density perturbations.

Initial isocurvature perturbations are in chemical content of massless quarks. Density perturbations are generated rather late after the QCD phase transition. **The mechanism is very much different from other conventionl ones.**

The emerging universe looks like a piece of Swiss cheese, where holes are high baryonic density objects occupying a minor fraction of the universe volume.

Results

- PBHs with log-normal mass spectrum - **confirmed by "experiment"!**
- Strange stars in the Galaxy with unusual chemistry and velocity.
- Disperse hydrogen and helium clouds with (much) higher than average n_B density.
- β **may be negative leading to creation of (compact?) antistars which could survive annihilation with the homogeneous baryonic background.**
- Extremely old stars would exist even, "older than universe star" is found; the older age is mimicked by the unusual initial chemistry. Several too old stars are observed.

The mechanism of PBH creation pretty well agrees with the data on the mass spectrum and on existence of antimatter in the Galaxy, especially of antistars. So we may expect that it indeed solves the problems discovered by HST and JWST.

Primordial black holes that have seeded galaxy formation remove tension between ΛCDM cosmology and astronomical data.
A byproduct of the model of PBH formation predicts and explains the origin of the observed antimatter population of the Milky Way